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## Quantitative analysis of future scenarios of urban mobility using agent-based simulation – A case study

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### Abstract

Nowadays, urban mobility is facing many challenges such as efficiency, eco-friendliness, and comfort, for instance. Growing cities and not least the discussion about vehicular emissions and climate change are calling for adequate solutions for the existing problems in urban transport. However, because of many reasons including diverging interests, there is no consensus in politics and society at the moment about what these solutions should finally look like. For this purpose, using the example of the city of Berlin, three different future scenarios of urban mobility were simulated in detail by applying advanced tools for integrated agent-based modelling of traffic demand, traffic flow and vehicle emissions. While the first proposed scenario explicitly focuses on eco-friendliness and sustainability, a second one pursues a primarily economic-liberal concept. The third scenario represents a business-as-usual approach that, in particular, tries to find the balance between environmental, economic and social needs. Based on these scenarios, the effects of different political and societal priorities on urban mobility are then analyzed thoroughly with regard to traffic volumes, modal split, travel times, and CO<sub>2</sub> emissions. As a key result, realistic potentials and limitations of behavioral changes (e.g., mode choice) as well as possible CO<sub>2</sub> reductions based on electric mobility, for instance, are derived.

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## 1. Introduction

Urban mobility is changing and needs to change in order to meet future social requirements in terms of efficient and comfortable transport as well as reduced air pollution and noise. Moreover, climate change leads to an urgent need of reducing the CO<sub>2</sub> emissions of transport in general. In this context, electric mobility (cf. van Wee *et al.* 2012) and car sharing (cf. Firnkorn and Müller 2011) are just two current trends promoting a new way of individual transport that (under the assumption of renewable energies) is clean and efficient at the same time. Facilitating public and intermodal transport by suitable measures is another option that is often discussed (cf. Gärling and Schuitema 2007).

The research project “VEU – Verkehrsentwicklung und Umwelt” (Transport and the environment; see Henning *et al.* 2016) tried to analyze how traffic and its environmental impact evolve until the year 2040 depending on the general priorities of political and societal decisions in the meantime. For this purpose, three detailed mostly national scenarios describing different possible framework conditions for future transport were developed in a complex process (cf. Seum *et al.* 2017a/b). While one of them (called “Regulated Shift 2040”) is explicitly focusing on ecological friendliness and sustainability, a second one is more dedicated to an economic-liberal approach (called “Free Play 2040”). Finally, the third scenario (called “Reference 2040”) can be seen as an attempt of balancing out the contrary interests that are associated with the aforementioned scenarios.

The present contribution discusses the more local effects of these scenarios with regard to traffic in urban areas such as the German capital Berlin (see Figure 1) which was chosen for this case study. After a short description of the modelling approach (see Section 2), the relevant details of the considered scenarios are presented (see Section 3). The main focus will be on the analysis of the simulation results (see Section 4) addressing traffic volumes, modal split, average travel speeds, as well as aggregated vehicle emissions depending on the scenario assumptions. All findings are compared to a corresponding initial simulation of traffic demand and traffic flow based on empirical numbers for the year 2010 (called “Reference 2010”). The paper concludes with a short summary of the main observations including some general remarks with regard to possible consequences for political and societal decisions (see Section 5).

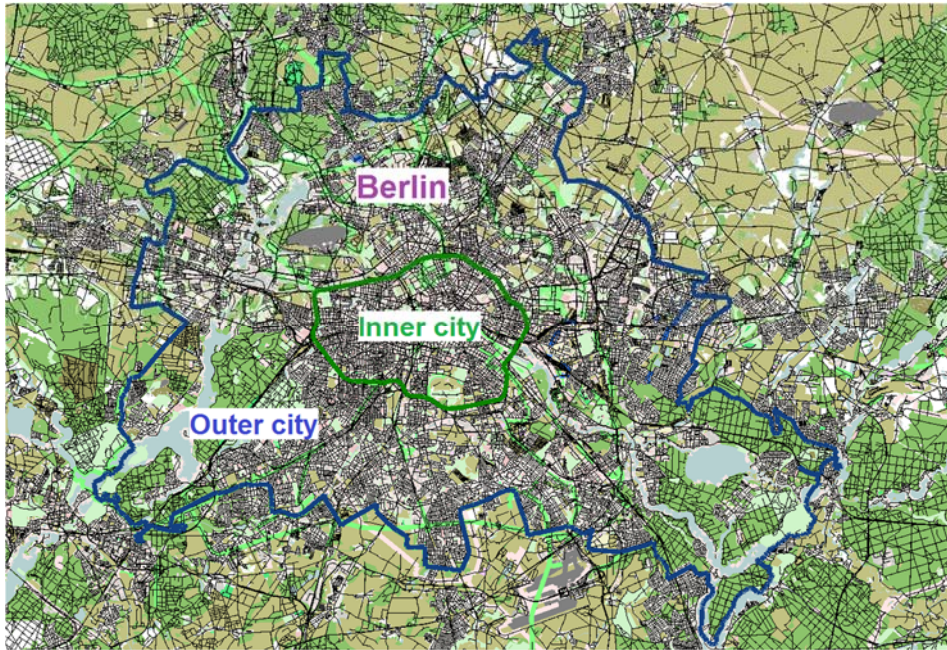


Figure 1. Study area.

## 2. Modelling Approach

The analysis in this case study is mainly based on microscopic and mesoscopic tools of traffic demand and traffic flow simulation. This includes generating a virtual population of the area under consideration (i.e., Berlin) and modelling the mobility behavior of people based on official demographic statistics and specific household surveys such as “Mobilität in Deutschland 2008” (see Lenz et al. 2010). The corresponding models used are the so-called SYNTHESIZER model (cf. von Schmidt et al. 2017) and the agent-based TAPAS (cf. Heinrichs et al. 2017). Road traffic assignment and traffic flow simulation are based on SUMO (see Krajewicz et al. 2012) which directly yields the trajectory inputs for emission modelling using PHEMlight (cf. Krajewicz et al. 2014). Note that the details of all these models cannot be explained here, but the reader may consult the above-mentioned literature instead.

### 2.1. Model Structure

The general model structure is depicted in Figure 2. As can be seen, there is a strong interaction between traffic demand modelling using TAPAS and traffic assignment (= traffic flow modelling) using SUMO (cf. Krajewicz et al. 2016). In fact, the integration between both models has resulted in a fully automatic coupling via a common database during the project. Moreover, there is a similar connection between SUMO and the emission model PHEMlight which exists as an integral module of the official SUMO software suite. Note that the TAPAS model focuses on passenger transport only. And, it is restricted to trips starting and ending in Berlin. Thus, commercial traffic as well as commuter road traffic from outside of Berlin was integrated from an external macroscopic model (cf. Winkler et al. 2017) in order not to disregard relevant portions of traffic during the assignment (cf. Figure 2). The only (minor) limitation is that people using public transport (including air transport) for travelling from outside of Berlin to one of the airports or train stations could not be considered in the model for technical reasons.

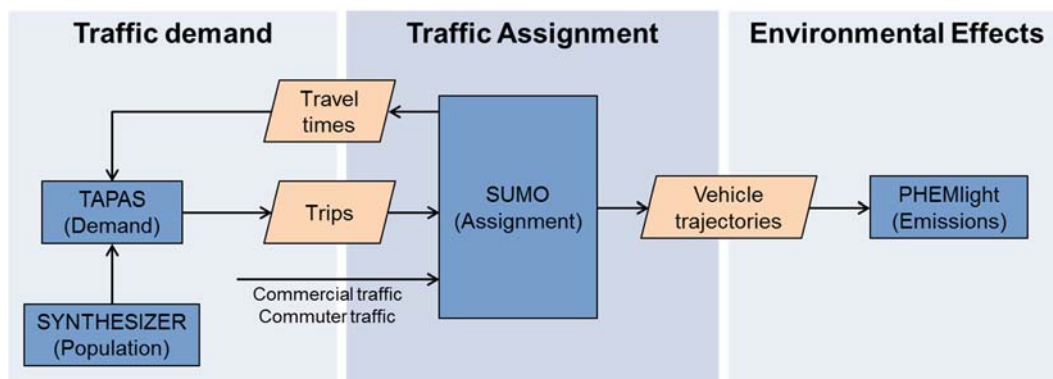


Figure 2. Model architecture.

## 2.2. Calibration

The calibration of the models used is a complex task that usually requires lots of data. Relevant parameters of traffic demand relate to the behavior of people in terms of destination and mode choice based on individual factors such as age, gender, income, or car availability (cf. Heinrichs et al. 2016). A list of data sources applied with regard to these and other aspects is given in Table 1. Further inputs for the traffic models are the line network of public transport<sup>†</sup> as needed for modelling accessibilities and route choice with regard to public modes, for instance, as well as a detailed representation of the road infrastructure for the micro-/mesoscopic road traffic assignment (cf. Figure 2). In this context, an existing digital road map<sup>‡</sup> was manually checked and – where necessary – corrected with regard to intersection layouts and number of lanes based on aerial images. Route choice as related to motorized individual transport was modelled in SUMO using an advanced and computationally efficient “fastest path” algorithm allowing for dynamic re-routing of vehicles during the assignment in dependence of simulated traffic conditions (cf. SUMO 2018). Finally, the vehicle-dependent emission curves used by the PHEMlight model are the result of extensive vehicle measurements continuously done by the model developers at the Institute of Internal Combustion Engines and Thermodynamics at TU Graz. Independent measurements with a small number of vehicles performed at the Institute of Vehicle Concepts at DLR further confirmed the validity of the emission model with regard to CO<sub>2</sub> as considered in Section 4.3.

Table 1. Data used for calibrating the traffic demand models.

Description	Data source	Year of reference	Link (URL)
Population forecast	Census 2011	2012	<a href="https://www.zensus2011.de/DE/Home/home_node.html">https://www.zensus2011.de/DE/Home/home_node.html</a>
Household distribution	Micro-census	2012	<a href="https://www.destatis.de/DE/ZahlenFakten/GesellschaftStaat/Bevoelkerung/MikrozensusInfo.html">https://www.destatis.de/DE/ZahlenFakten/GesellschaftStaat/Bevoelkerung/MikrozensusInfo.html</a>
Car fleet and prices	German Federal Transport Infrastructure Plan 2030	2015	<a href="https://www.bmvi.de/SharedDocs/DE/Artikel/G/verkehrsprognose-2030.html">https://www.bmvi.de/SharedDocs/DE/Artikel/G/verkehrsprognose-2030.html</a>
Mobility behavior	Ahrens 2009	2008	<a href="http://tu-dresden.de/die_tu_dresden/fakultaeten/vkw/ivs/srv/dateien/staedtepegel_srv2008.pdf">http://tu-dresden.de/die_tu_dresden/fakultaeten/vkw/ivs/srv/dateien/staedtepegel_srv2008.pdf</a>
Activity plans	Lenz et al. 2010	2008	<a href="http://mobilitaet-in-deutschland.de/pdf/infas_MiD2008_Abschlussbericht_I.pdf">http://mobilitaet-in-deutschland.de/pdf/infas_MiD2008_Abschlussbericht_I.pdf</a>

<sup>†</sup> <http://daten.berlin.de/kategorie/verkehr>

<sup>‡</sup> HERE Europe B.V., NAVSTREETS Data Germany, Map version: 2012 Q2

Calibration data

Ahrens 2014

2013

[http://www.berlin.de/senuvk/verkehr/politik\\_planung/zahlen\\_fakten/download/SrV\\_2013\\_Berlin\\_Tabellen.pdf](http://www.berlin.de/senuvk/verkehr/politik_planung/zahlen_fakten/download/SrV_2013_Berlin_Tabellen.pdf)

It is clear that a full validation of all the models from Figure 2 on a microscopic level is hardly possible because of missing reference data and large variations among the individual behavior of people. Besides comparing simulated modal splits with dedicated statistics (cf. Heinrichs et al. 2016), it seemed to be appropriate to compare the link-based traffic volumes, which are one of the main and final outputs of traffic demand and assignment modelling, with real-world measurements. Needless to say, this kind of validation can be done for the initial simulation (i.e., “Reference 2010”) only, but not for the future scenarios. Figure 3 exemplarily shows the simulated daily curves of traffic volume referring to a common working day for some links of the considered road network of Berlin. The reference curves are the average traffic volumes measured by stationary detectors at the corresponding locations. Quantiles are depicted as well representing the (quite large) daily variations of traffic flow as derived from the measurements based on data for several weeks.

Taking into account these normal variations, the SUMO results are in good agreement with the measurements even if there are examples (not shown here) where the fit is much worse. Also, the different characteristics of the curves as an effect of opposing commuting flows in the morning and during the late afternoon are simulated well. Thus, despite (or even because of) the complexity of the modelling approach from Figure 2, it can be concluded that the integrated traffic simulation provides quite plausible and reliable results, in general. Note that 80% of all considered links yield a correlation coefficient greater than 0.8 between simulated and measured traffic volumes, for instance. In 50% of all cases, the correlation coefficient even exceeds the value of 0.9. The sample in this context comprises 731 measuring sites spread all over Berlin. Figure 4 shows the corresponding spatial distribution of the detector locations.

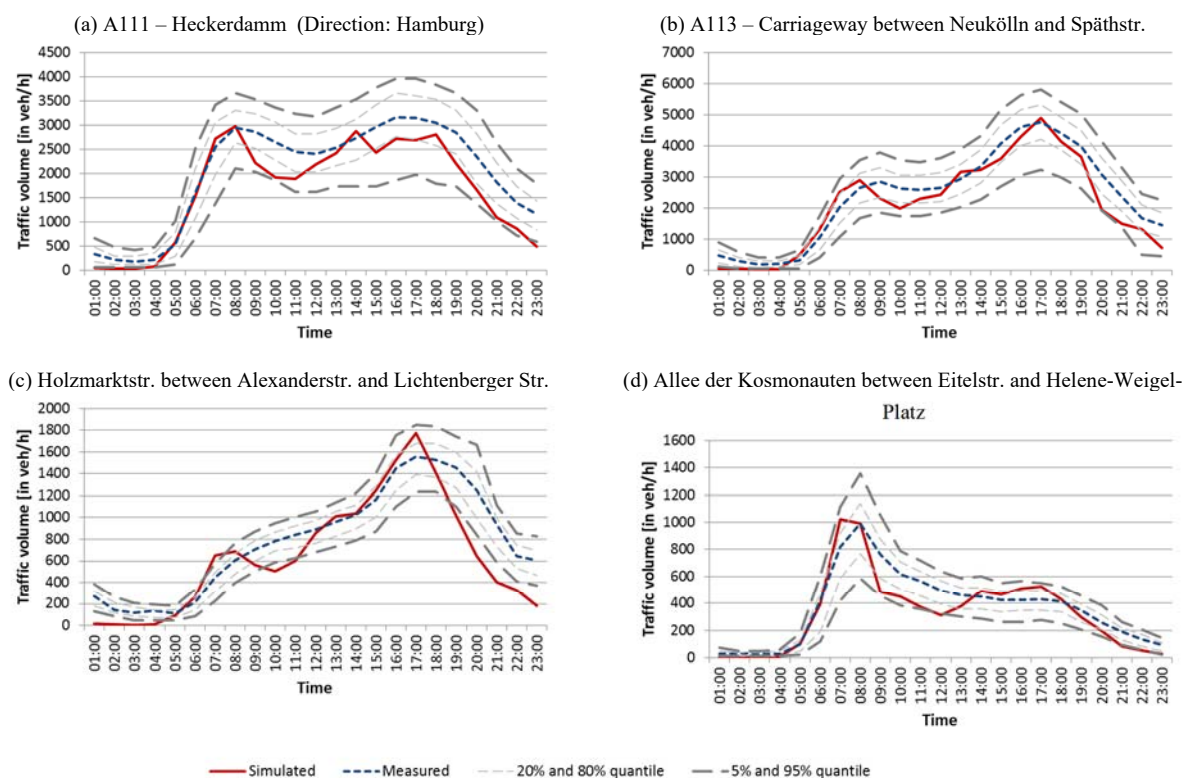


Figure 3. Simulated and measured traffic volumes: (a) & (b) Freeway; (c) & (d) Urban road.





Figure 4. Locations of the stationary detectors (dots) used for validating the simulated traffic volumes. (Small circles show the locations of the measuring sites as considered in the examples from Figure 3.)

### 3. Scenarios

As already mentioned in the introduction (see Section 1), three future scenarios of urban mobility were simulated and analyzed in comparison to each other in this study based on an initial simulation of the year 2010. All scenarios in this context refer to the existing road network of Berlin with only slight modifications in terms of additional links in the year 2040 (cf. Figure 5), those are in agreement with official road infrastructure plans. Concerning public transport, it is further assumed that possible increments of ridership can be managed by the available transport capacities in each scenario without modelling them in detail. Finally, based on the original forecast of the census 2011 (cf. Table 1), the population of Berlin was assumed to slightly grow by about 100.000 inhabitants between 2010 and 2040 reaching a number of 3.4 million<sup>§</sup> people in 2040.

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<sup>§</sup> In fact, Berlin was growing faster than expected since 2010. At the time of writing this article, there were about 3.6 million inhabitants.

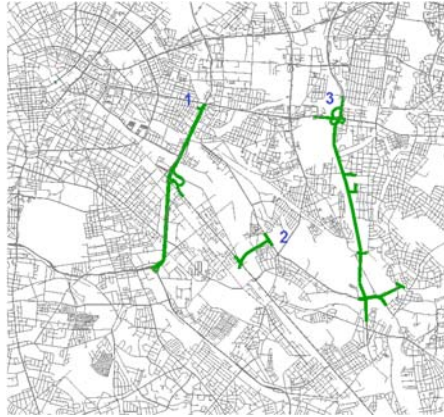


Figure 5. Considered modifications of the road network until 2040: 1) Extension of the freeway A100 between Neukölln and Frankfurter Allee; 2) Additional link between Köpenick and Treptow crossing the river Spree; 3) Additional bypass road in the eastern part of Berlin.

In the following, short descriptions of the future scenarios are given which also includes explicit numbers for the most crucial parameters affecting traffic demand and traffic flow. More detailed discussions of the scenarios with a more national (instead of urban) focus can be found in Seum et al. 2017b or Seum et al. 2018.

### 3.1. Reference 2040

The “Reference 2040” scenario can be seen as a kind of business-as-usual approach. That is, its main idea is based on balancing out the diverging interests formulated by different societal groups without significantly changing current guidelines in politics. While avoiding too heavy burdens on economy, moderate efforts towards a more sustainable transport system are made. Among other things, this is reflected by slightly decreasing travel times (–10% compared to 2010) as well as better access to public transport (4.6% time savings for the way to the next station or bus stop) at the cost of higher ticket prices (+1% p.a.). In addition, increased parking fees (+50% compared to 2010) are charged at the whole inner city of Berlin (cf. Figure 1) for individual transport. Car sharing is assumed to be available at moderate costs (64 ct/km). Finally, the total number of private cars in Berlin is set to 1.4 million which corresponds to a motorization rate of 42% with 62% of all households having a car. The modelled composition\*\* of this vehicle fleet as classified by engine types is shown in Figure 6 in comparison to the modelled fleet of 2010.

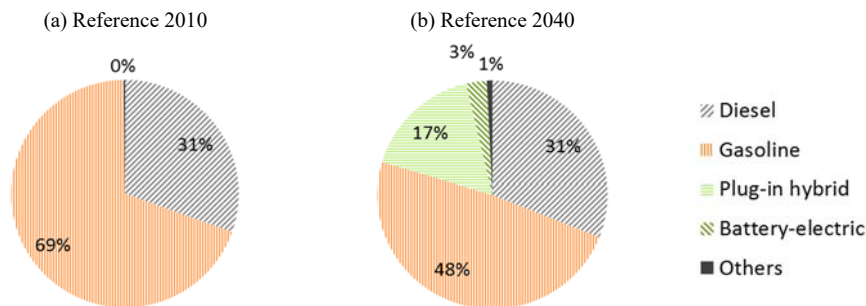


Figure 6. Composition of the vehicle fleet (private cars) in the reference scenarios: (a) 2010; (b) 2040.

\*\* Note that the presented numbers do not take into account the current discussion about bans on (also privately owned) diesel-powered cars.

### 3.2. Regulated Shift 2040

Under the assumption of scarce fossil resources and global cooperation in politics in the face of current environmental challenges, the scenario “Regulated Shift 2040” implements strategies with the explicit goal of a more sustainable and eco-friendly transport system. In this, it is quite ambitious but still realistic concerning the proposed measures. At the urban level, it is mainly characterized by an increased attractiveness of public transport with significantly reduced travel times (–20% compared to 2010) as well as decreasing ticket prices (–1% p.a.). Time savings for the way to the next station or bus stop in public transport are assumed to be about 4.6% as in the reference scenario (cf. Section 3.1). Also (free floating) car sharing is available everywhere in the city at moderate costs (64 ct/km). Then, in order to finance the improvements of public transport, travel costs for private cars are increased by introducing a distance-based toll (4 ct/km) together with higher parking fees (+100% compared to 2010) that are charged at the whole inner city (cf. Figure 1). Moreover, there is a complete ban on commercial diesel-powered vehicles for the same area.

In contrast, cycling is facilitated by building new dedicated cycle tracks with a hypothetical average reduction of travel times (–16.7% compared to 2010) for cyclists. The space for such tracks (as well as for raising the capacities of public transport) is taken from individual road transport by conversion of one traffic lane on each road (except freeways) with two or more lanes in the original network. In addition, road capacities for individual transport are further reduced by introducing an area-wide urban speed limit of 30 km/h on all roads except for freeways and main arterials. Finally, with regard to the vehicle fleet, a strong shift towards electric mobility as an effect of extended subsidies is assumed (cf. Figure 7) even though fossil fuels are still dominant for the hypothetical number of 1.2 million private cars (i.e., motorization rate = 35% with 54% of all households having a car). The disproportional decrease in the number of diesel-powered vehicles (cf. Figure 7), by the way, can be seen as an effect of higher taxes on such engine types and on diesel fuels.

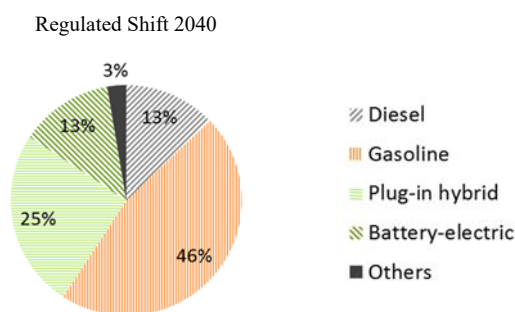


Figure 7. Composition of the vehicle fleet (private cars) in the “Regulated Shift 2040” scenario.

### 3.3. Free Play 2040

In contrast to the explicit eco-friendliness of the aforementioned scenario (see Section 3.2), the “Free Play 2040” scenario pursues an economic-liberal approach with a more competitive political environment that primarily focuses on national prosperity. In that way, it is not necessarily a negative opposite of the (green) “Regulated Shift 2040”, but it just gives priority to other important factors influencing people’s well-being. However, innovative (green) technologies and mobility concepts become available at a larger scale only if they allow for making profits at the end. This, for instance, also means that current subsidies for public transport are reduced as far as they are used for just keeping inefficient lines or systems alive. Thus, travel times in public transport are assumed to increase by 10% compared to 2010 in the following with no time savings for the way to the next station or bus stop. At the same time, ticket prices rise by 2% p.a. hypothetically.



With regard to individual traffic, no specific restrictions are considered except for parking fees (+100% compared to 2010) charged at the whole inner city (cf. Figure 1) in order to avoid a potential traffic collapse in the city center when capacities of public transport are removed. Car sharing, by the way, is available as in all other scenarios, but at higher costs (70 ct/km). Finally, since fossil fuels are assumed to be less scarce in the “Free Play 2040”, no major changes in the vehicle fleet compared to 2010 are expected (cf. Figure 8). In this context, the number of private cars is raised to 1.5 million in this scenario reflecting a motorization rate of 45% with 64% of all households having at least one car.

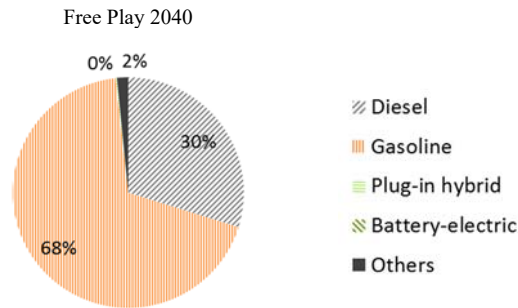


Figure 8. Composition of the vehicle fleet (private cars) in the “Free Play 2040” scenario.

#### 4. Simulation Results

Using the calibrated models from Section 2, all described scenarios were simulated in detail. The following subsections discuss the results with regard to modal split and traffic volumes for all modes as well as travel speeds and CO<sub>2</sub> emissions for individual road traffic, in particular. A specific focus will be on explaining the interconnections between the individual findings against the background of the scenario settings.

##### 4.1. Traffic volumes and modal split

Figure 9 shows the simulated traffic volumes for a typical working day in Berlin in the case of the described scenarios. As can be seen, the total volumes increase in all three scenarios compared to 2010 which is mostly because of the assumption that the population of Berlin will continue to grow slightly until 2040. Interestingly, the increase of traffic volume is lowest in the economic-liberal scenario (“Free play 2040”). The figures (i.e., the small share of public transport) imply that this is a result of a less powerful public transport, in particular, where financial subsidies for inefficient lines are reduced and prices rise according to the scenario definition. Consequently, car mobility significantly gains weight while mobility options for people without access to a personal car dwindle, in general. Car sharing does not play an important role.

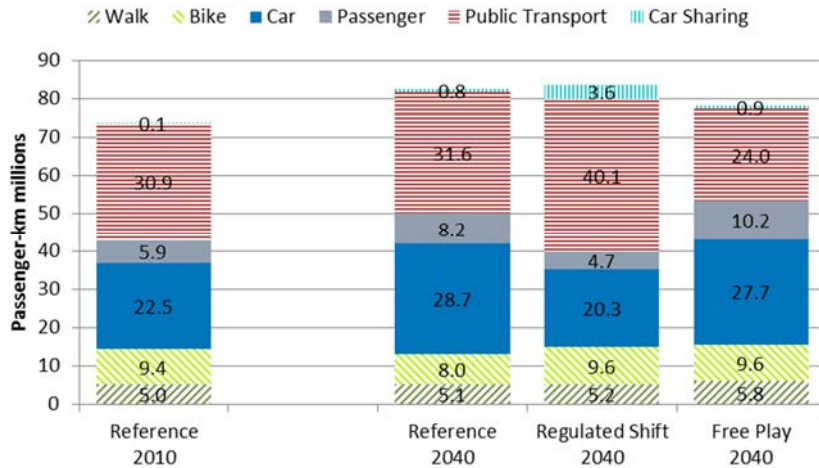


Figure 9. Simulated traffic volumes.

On the contrary, most of the additional traffic demand in the “Regulated Shift 2040” scenario is managed by public transport as an effect of reduced travel times and low ticket prices. However, also in this scenario, the total traffic volumes associated with car traffic (i.e., car + passenger + car sharing) do not decrease in comparison to 2010 despite severe measures (such as significant reductions of road capacities and distance toll for private users) in that scenario trying to make individual transport less attractive. But, it seems that car sharing takes a significant share (i.e., about 13%) of all car-related passenger-kilometers in this case. With regard to the modal split, even every fifth car trip is done by car sharing in the “Regulated Shift 2040” (cf. Figure 10).

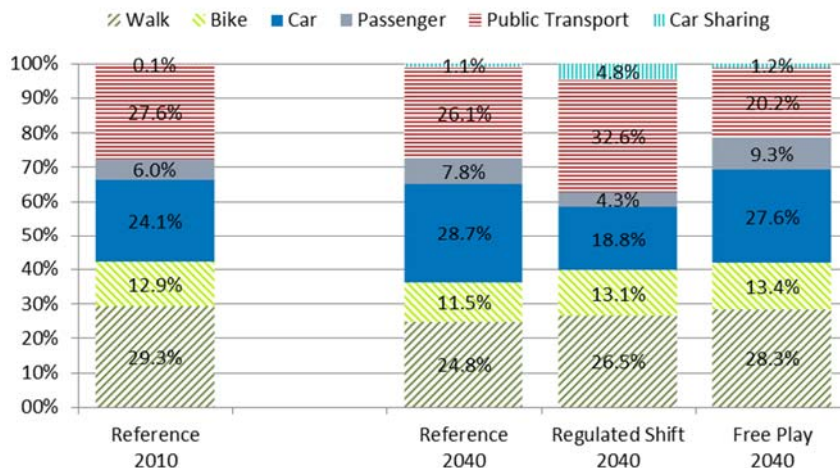


Figure 10. Simulated modal split.

Finally, a quite interesting result is that walking and cycling in the “Free Play 2040” scenario has at least the same weight as in the “Regulated Shift 2040” (cf. Figure 9 and Figure 10) even if there are no specific measures to foster it. Among other things, this is explained by the different average costs for mobility of private users in both scenarios. Figure 11 shows these costs divided into its relevant components. It turns out that the “Free Play 2040” is the most

expensive scenario for private users. That is, together with the decline of public transport and the high parking fees in the inner city, walking and cycling become an attractive (or even inevitable) alternative to travelling by car for short distances in the city center (cf. Figure 12b) depending on the individual income. For longer distances outside the city center, however, car traffic remains the most important mode.

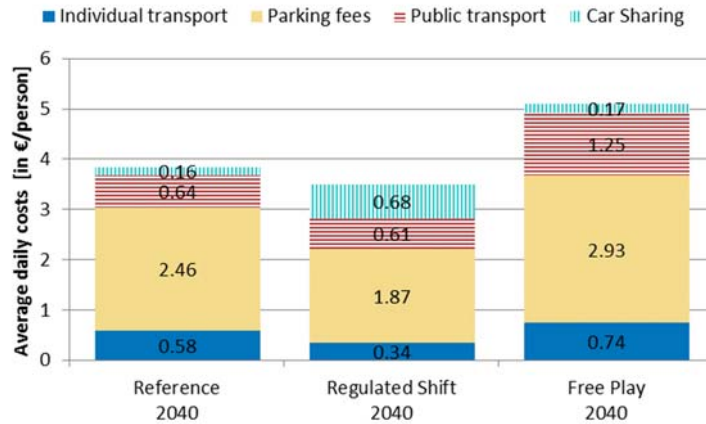


Figure 11. Simulated average costs for urban mobility of private users per day.

In the “Regulated Shift 2040”, the attractiveness of cycling mainly comes from reduced travel times and a better infrastructure instead of external restraints. Consequently, cycling becomes a serious alternative to travelling by car also for medium distances on tangential relations outside the city center where the center-oriented public transport system of Berlin traditionally has some weaknesses. On the other hand, there is no such an increase of cycle trips in the inner city (cf. Figure 1) where an efficient public transport (cf. Section 3.2) seems to undermine the trend towards more cycle traffic (cf. Figure 12a).

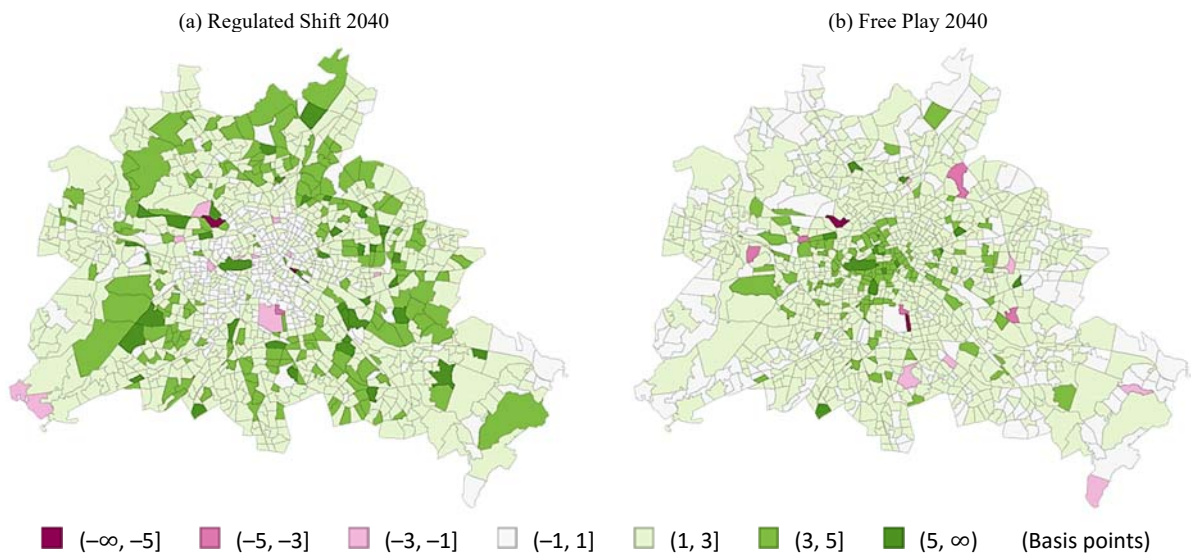


Figure 12. Detailed differences of the modal split with regard to cycle traffic compared to “Reference 2040”.

#### 4.2. Travel times and travel speeds

According to the different development of traffic demand and modal split in the considered future scenarios (cf. Section 4.1) as well as because of a significant reduction of road capacities in the “Regulated Shift 2040” (see Section 3.2), also traffic flow (i.e., travel speeds) on the roads can be expected to differ in the scenarios because of more or less heavy congestions across the day possibly resulting in quite different travel times among the scenarios. Figure 13a shows the simulated average travel speeds (= total distance travelled / accumulated travel time of all vehicles) as normalized version of the distance-dependent travel times for Berlin. A more detailed plot of the corresponding daily curves is given in Figure 13b.

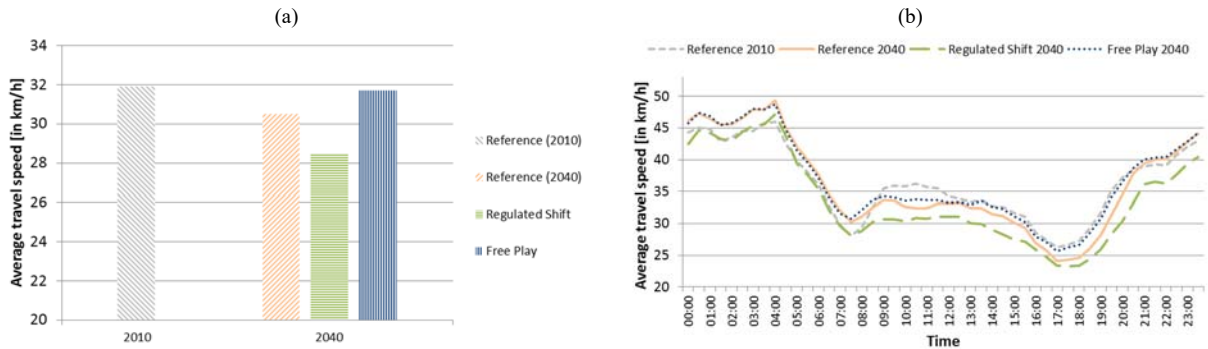


Figure 13. Simulated average travel speeds for individual road traffic: (a) Daily average; (b) Half-hourly values.

As can be seen, there are only small (or even no) changes between 2010 and 2040 in the “Reference” (–1.4 km/h) as well as the “Free Play” scenario (–0.2 km/h). The slightly diverging behavior in this case is explained by the previously discussed variations among the corresponding traffic volumes (cf. Figure 9). On the contrary, note that travel speeds decrease more significantly in the “Regulated Shift 2040” (–3.4 km/h) as a consequence of the systematic reduction of road capacities. This means that the “green” scenario eventually produces even more road congestion than the “Reference 2010” despite of more or less the same car traffic volumes (cf. Section 4.1). But, this slackening of private transport seems to be a necessary prerequisite for effectively raising the share of public transport in the modal split (cf. Figure 10) according to the modelled mode choice behavior.

#### 4.3. Emissions

With regard to the tank-to-wheel CO<sub>2</sub> emissions of individual road traffic, Figure 14 shows the aggregated PHEMlight results for a typical working day in Berlin in the case of the considered scenarios. The highest reduction (compared to 2010) is obtained in the “Regulated Shift 2040”. Having in mind that the car traffic volumes do not decrease even in this scenario (cf. Section 4.1), it becomes clear that (under the assumption of renewable energies) most of the CO<sub>2</sub> reduction comes from improved technologies and electric mobility which have their highest share in the “Regulated Shift 2040” scenario (cf. Figure 7). Changes of the mobility behavior of people, in the best case, just helps to avoid additional traffic (and thus additional emissions) on the roads by keeping car traffic volumes (i.e., car + passenger + car sharing) constant over the years.

In the “Free Play 2040” scenario, technological gains (e.g., because of more efficient engines) in terms of CO<sub>2</sub> reductions finally come to nothing as a consequence of more traffic on the roads (cf. Figure 9) resulting in more or less constant emissions at a high level. The slight decrease of the emissions in the “Reference 2040” scenario in this context simply originates from the higher share of alternative engine types compared to “Free Play 2040” (cf. Figure 6), rather than from changes of the behavior of people.

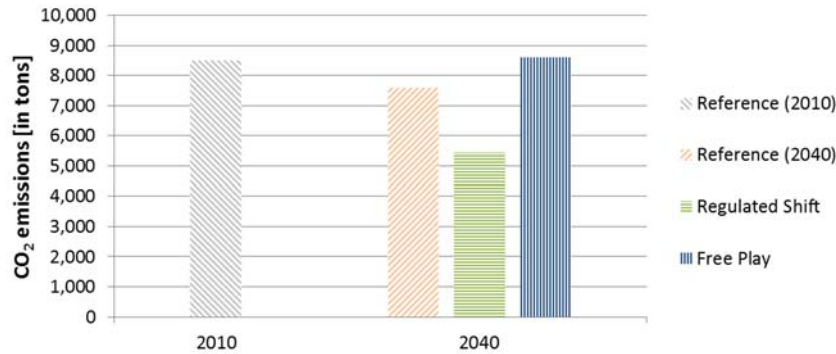


Figure 14. Simulated tank-to-wheel CO<sub>2</sub> emissions of individual road traffic per day (whole Berlin).

Again, it is interesting to see how the numbers differ spatially. For this purpose, Figure 15 shows some more detailed values. As an effect of increased parking fees (and thus reduced car traffic) together with a more or less efficient public transport, the CO<sub>2</sub> reductions turns out to be much higher in the inner city, in general. Moreover, note that in the case of the “Free Play 2040” scenario the increasing cycle traffic in this area (cf. Figure 12b) further decreases the emissions a little. In contrast, the average reductions of CO<sub>2</sub> are much smaller outside the city center with even an increase by 4% for the economic-liberal approach. This mostly results from a less strong public transport in the outer city (compared to the inner city) in all scenarios which generally pushes the modal split towards more individual transport modes (i.e., car traffic, in particular) in these areas. Even the strengthening of cycle traffic as found for the “Regulated Shift 2040” scenario (cf. Section 4.1) is not able to completely compensate for this effect. Nonetheless, a simulated CO<sub>2</sub> reduction of about 32% (compared to 2010) can be expected also outside the city center by implementing the presented “green” scenario.

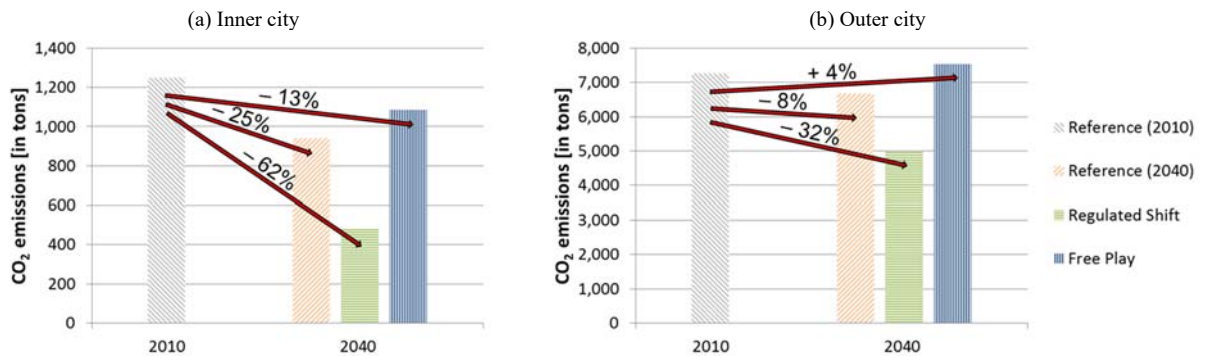


Figure 15. Breakdown of simulated tank-to-wheel CO<sub>2</sub> emissions of individual road traffic per day: (a) Inner city; (b) Outer city.

## 5. Conclusion

Depending on the priorities of political and societal decisions in the scenarios considered in this case study, urban traffic is expected to evolve quite differently in the future. In this context, CO<sub>2</sub> reductions (tank-to-wheel) will probably be mostly an effect of technological innovations and a more or less strong electric mobility (under the assumption of renewable energies). On the other hand, the simulated changes of people’s mobility behavior (cf. Section 4.1) without considering technological improvements seem to be able to compensate for generally increasing



traffic volumes only, but do not really solve the current environmental problems. In this context, the “green” scenario turns out to be even the least attractive one with regard to road traffic flow and travel speeds even if it is to be preferred from an ecological perspective.

Overall, the presented results in this study yield a consistent in-depth picture of future mobility in urban regions such as Berlin based on detailed micro-/mesoscopic simulations of traffic demand, traffic flow and vehicle emissions. Needless to say, all findings strongly depend on the validity of the empirically derived (more or less conservative) behavioral models that are used. Even if much effort was put into calibrating the models (cf. Section 2.2), new social trends and/or alternative transport options in terms of vehicles and infrastructure may, of course, change the stated behavior of people. Valid simulation results of this, however, would require further detailed empirical studies and additional surveys first in order to derive suitable parameters for the respective behavioral models. A good starting point for such dedicated research could be the experiences of cities with (currently or traditionally) different mobility behavior compared to Berlin (cf. Langeland 2015).

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